Final Report

Title: Effect of flexibility on flapping propulsion

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14. ABSTRACT
The main objective of the work was to understand the effect of flexibility on flapping foils. Flexibility is inevitably present, though, to different degrees, in the wings of many natural fliers and in the fins and tails of fish. The loads on such foils are related to the circulations developed around the foils and indirectly to the circulations in the vortices that are shed in the wake. The foils and fins in nature are three dimensional and the interactions between the fluid and the flexible surfaces complex. The present study was aimed at having a simple experimental model to study the effect of flexibility on the flow. Towards this end we studied the flow field due to a pitching 2-dimensional NACA 0015 foil, to which was attached flexible flap. Two types of experiments were conducted with the flapping foil to which was attached a flexible foil. One was with forward motion or with a free-stream velocity. The other was in stationary fluid. In the first set, flow fields were investigated using dye visualization and PIV for flapping foils with and without the flap. The flexible flap substantially changed the flow field. In the second set, i.e., flow generated without free stream, in stationary water, a new type of hovering mechanism was discovered.

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Final Technical Report

Objectives:

The main objective of the work was to understand the effect of flexibility on flapping foils. Flexibility is inevitably present, though, to different degrees, in the wings of many natural fliers and in the fins and tails of fish. The loads on such foils are related to the circulations developed around the foils and indirectly to the circulations in the vortices that are shed in the wake. The foils and fins in nature are three dimensional and the interactions between the fluid and the flexible surfaces complex. The present study was aimed at having a simple experimental model to study the effect of flexibility on the flow. Towards this end we studied the flow field due to a pitching 2-dimensional NACA 0015 foil, to which was attached flexible flap. .

Status of effort:

The studies gave new information on the effect and role of flexible flap attached to the trailing edge of a rigid pitching airfoil. This information mainly has come from flow visualization and detailed PIV measurements for the pitching foil with a certain free stream velocity and in stationary fluid. The experiments were conducted in water, but the results may be extended to pitching foils in air. In the cases with free stream velocity the following observations could be made: i) the wake of the foil with the flexible flap contained many weak vortices per half cycle of oscillation in comparison to the wake with a rigid trailing edge which had one strong vortex per half cycle; ii) the wake in the former case remained two dimensional for a longer time. (See appendix below.)

The main new progress was made with regard to the experiments of pitching foil in a stationary fluid (with no forward motion). Here we found a new type of flow, which consisted of a coherent jet with reversed Karman street of vortices. The implication of jet formation is that thrust is generated in a stationary fluid, and thus corresponds to hovering type of motion found in birds and insects. However, the mechanism in our experiments is very different from the ones observed in birds and insects. Thus this seems to be novel mechanism of hovering. (See attached ICIUS paper.)

Abstract:

Two types of experiments were conducted with the flapping foil to which was attached a flexible foil. One was with forward motion or with a free-stream velocity. The other was in stationary fluid. In the first set, flow fields were investigated using dye visualization and PIV for flapping foils with and without the flap. The flexible flap substantially changed the flow field (see appendix below for details). In the second set, i.e., flow generated without free stream, in stationary water, a new type of hovering mechanism was discovered.(see attached papers.)

Personnel Supported:

i) Sachin Shinde, PhD Graduate student
ii) Achut Bhure, Master’s student

Publications:

1) Shinde, S.Y., and Arakeri, J. H. The effect of chordwise flexibility on flapping foil propulsion in quiescent fluid, 63rd Annual meeting of the American Physical Society's Division of Fluid Dynamics (APS-DFD), 21--23 November 2010, Long Beach, California, USA.

2) Arakeri, J. H., and Shinde, S. Y. A novel hovering mechanism from a flapping two-dimensional flexible foil, International conference on Intelligent Unmanned Systems (ICIUS), 3--5 November 2010, Bali, Indonesia.

3) Shinde, S.Y., and Arakeri, J. H. A new type of hovering from a flapping flexible foil, 6th World Congress on Biomechanics (WCB), 1--6 August 2010, Singapore.

Interactions:

(a) Participation/presentations at meetings, conferences, seminars, etc.
Conferences attended:

6th World Congress on Biomechanics (WCB), 1--6 August 2010, Singapore.
International conference on Intelligent Unmanned Systems (ICIUS), 3--5 November 2010, Bali, Indonesia.
63rd Annual meeting of the American Physical Society's Division of Fluid Dynamics (APS-DFD), 21--23 November 2010, Long Beach, California, USA.

(b) Knowledge resulting from your effort is used, or will be used, in a technology application. Maybe used for developing mechanism for hovering.

Inventions:

(a) Discoveries, inventions, or patent disclosures: None

(b) Complete the attached **"DD Form 882, Report of Inventions and Subcontractors."**

Honors/Awards: List honors and awards received during the contract period, or emanating from the AOARD-supported research project: None.

Archival Documentation: Please see attached papers and appendix below.

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Appendix: Effect of flexibility on flapping propulsion; case with forward motion

Recently, the use of oscillating foils as propulsors has attracted much interest due to demand of increased efficiencies and quietness of autonomous underwater vehicles. The inspiration for this stems from aquatic animals. A few among the many payoffs of using oscillating propulsors are noiseless wake which may be advantageous for defense applications, increased propulsive efficiency, and increased maneuverability.

The present work aims to the study of the flow due to an oscillating airfoil. We have used two models - one is a rigid airfoil NACA0015 section without any flap and the other is with a flexible flap attached at the trailing edge. The airfoil with the flap at the trailing edge is called as model-A and the airfoil without flap is called as model-B.

We study the flap motion, flow around the flap as well as the wake structure in terms of vortex spacing, evolution of vortices, etc. The wakes generated by model-A and model-B are compared. From literature, it is found that the propulsive efficiency is maximum for Strouhal number (St) range 0.2 to 0.4 for oscillating airfoils as well as many swimming and flying animals (Taylor et al. 2003 and Triantfyllou et al. 1991). So a Strouhal number close to 0.3 is chosen in the experiments. Amplitude of oscillation is fixed as 10^0 and frequency of oscillation as 3 Hz. The forward speed is adjusted such that the St comes around 0.3. Strouhal number is defined as,

$$St = fA/U$$

where,

f = frequency of oscillation,
A = lateral excursion of the airfoil trailing edge,
U = forward speed.

Since it is difficult to get exactly same speed each time from the DC motor driving the airfoil forward, a variation of St in a narrow range of 0.06 is obtained. Particle visualizations and PIV (Particle Image Velocimetry) is carried out which helped in finding the wake parameters. Using dye visualizations, we obtain more information about the formation and evolution of vortices. Our zone of interest in the experiment is approximately 180 mm along the path of the airfoil over which the circular path can be approximated to a straight-line path and curvature effects can be neglected.

3. RESULTS & CONCLUSION

The notations, conventions and the cases are listed in Table 1.

The flow around model-B, i.e. airfoil without flexible flap at the trailing edge, shows the formation of large vortices. One vortex is shed per half cycle. The alternate vortices have opposite signs. These vortices are spaced very close to the mean path of travel indicating a momentumless wake. For all the cases (f=1 Hz, 2 Hz, 3 Hz and amplitude=10^0 and 20^0) the vortex evolution is similar. The flow visualizations are shown for set-1 and set-3 in figures 2 and 3 respectively.

Next we consider model-A, airfoil with the flexible flap. Since the flap is very thin it can be considered to have negligible mass and stiffness. In all the cases the flap deflections are considerable and are more than the trailing edge deflections. Figures 4(a) and 4(b) show the deflections of flap tip and trailing edge against pitch angle for set-1 and set-2 respectively. It is found that the trailing edge deflection leads the flap tip deflection approximately by 135^0. This phase difference remains almost same for all the frequencies studied with amplitude 10^0. Figures 5(a) and 5(b) show the flap tip and trailing edge deflections against pitch angle for set-3 and set-4 respectively. The phase difference is found close to 90^0 for amplitude 20^0 with trailing edge deflection leading the flap tip deflection. This phase difference remains nearly the same for all the frequencies studied for 20^0 amplitude. For a given amplitude of oscillation (10^0 or 20^0), the flap tip deflection is same for all the frequencies. More analysis is needed to explain the flap behaviour. The authors are trying to propose a relation for the phase difference between flap tip and trailing edge deflections.

The wake for model-A i.e. airfoil with the flexible flap at the trailing edge is considerably different from the wake of model-B in terms of vortex spacing and in the number of vortices shed per cycle. Instead of large vortical structures (as found in case of the wake of model-B), small multiple vortices are generated in the wake of the airfoil with the flap. The wake dies out faster in this case. This may be because of the multiple small vortices compared to the large vortical structures generated by the rigid trailing edge. The comparison between figure 6 (set-1) and figure 7 (set-2) shows that the wake width and number of multiple vortices reduce as the frequency increases. A similar trend is observed in case of 20^0 amplitude (see figure 8-(set-3) and figure-9(set-4)). So it can be said that the wake width and number of multiple vortices reduce as frequency increases for the same amplitude. The wake widths of model-A and model-B are of the same order, even though the total chord is 70 mm for model-A compared to 40 mm for model-B.

The vortices are spaced away from the mean path indicating that the thrust and drag on the airfoil are not equal i.e. the wake is not momentumless. In case of rigid trailing edge the wake is found to be almost momentumless for nearly the same Strouhal number.

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Taylor G. K., Nudds R. L. and Thomas A. L. R. 2003 *Flying and swimming animals cruise at a strouhal number tuned for high power efficiency,* **Nature 425, 707-710.**

Triantfyllou M. S., Triantfyllou G. S. and Gopalkrishnan R. 1991 *Wake mechanics for thrust generation in oscillating foils,* **Physics of fluids A(3), 2835-2837.**

Model-A	Airfoil with flexible flap at the trailing edge.
Model-B	Airfoil without flexible flap.
Set-1	Amplitude of oscillation=$10^{\mathbf{0}}$, frequency of oscillation=1 Hz
Set-2	Amplitude of oscillation=$10^{\mathbf{0}}$, frequency of oscillation=3 Hz
Set-3	Amplitude of oscillation=$20^{\mathbf{0}}$, frequency of oscillation=1 Hz
Set-4	Amplitude of oscillation=$20^{\mathbf{0}}$, frequency of oscillation=3 Hz
+	Clockwise rotation of the vortex
-	Counter-clockwise rotation of the vortex
Positive deflection	Trailing edge and flap tip deflections above the mean path
Negative deflection	Trailing edge and flap tip deflections below the mean path

Table 1: Notations and conventions used in analysis.

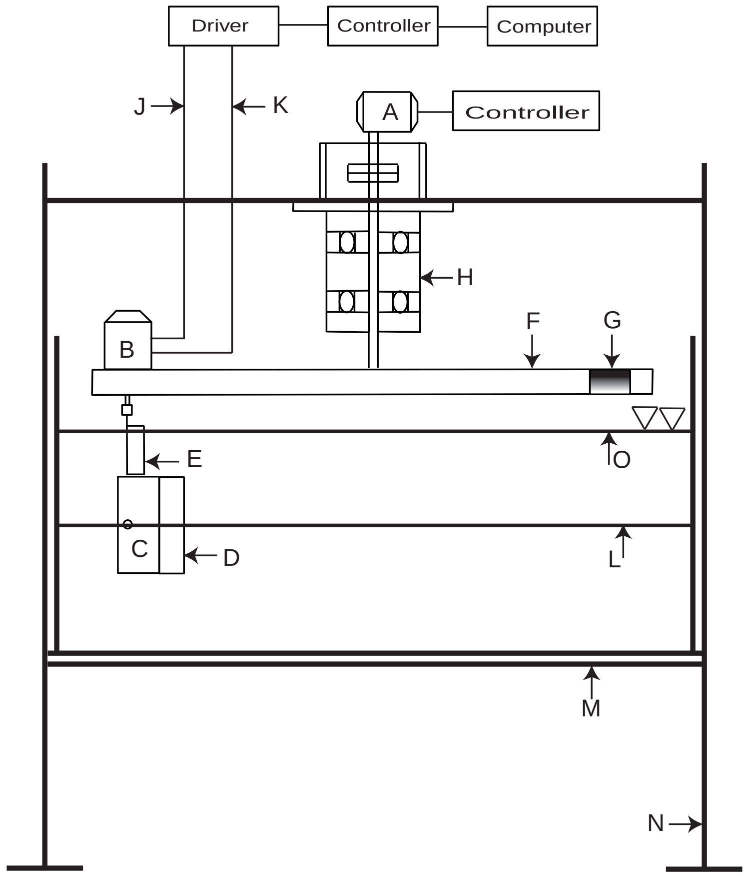
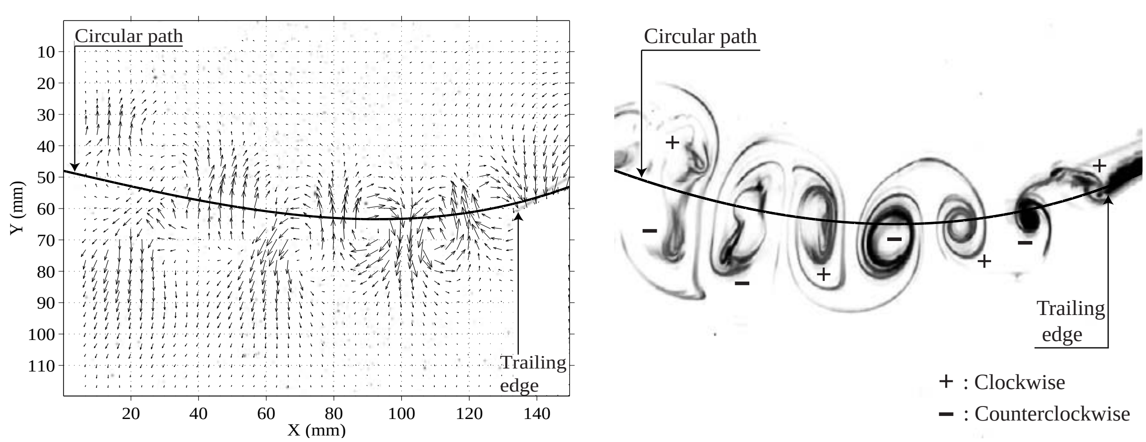


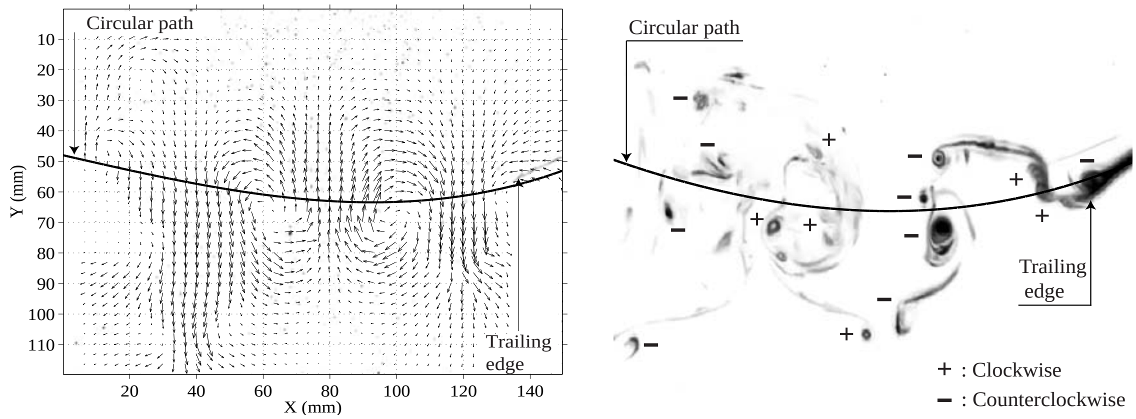
Figure 1: Schematic diagram of the experimental set-up. Notations:- A-DC motor, B-servo motor, C-airfoil, D-Flap, E-small airfoil, F-rotary arm, G-counterbalance weight, H-bearing housing, J-encoder cable, K-motor cable, L-plane of visualization, M-glass tank, N-frame, O-water level.



(a) **(b)**

Figure 2

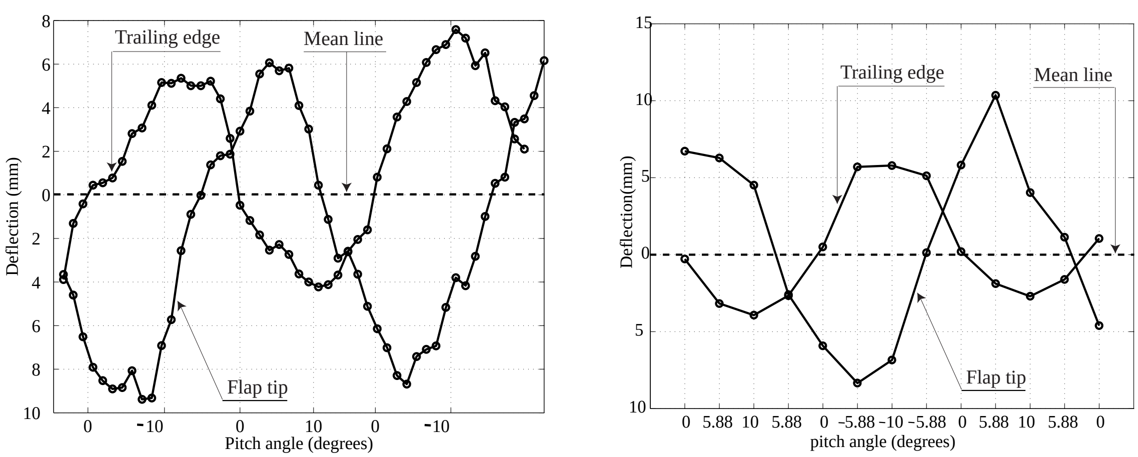
(a): **PIV image: model-B. f=1 Hz, amp=10^0, U=3.71 cm/sec, St=0.35**
(b): **Dye visualization: model-B. f=1 Hz, amp=10^0, U=4.56 cm/sec, St=0.29**



(a) **(b)**

Figure 3

(a): **PIV image: model-B. f=1 Hz, amp=20^0, U=8.20 cm/sec, St=0.31**
(b): **Dye visualization: model-B. f=1 Hz, amp=20^0, U=8.05 cm/sec, St=0.32**

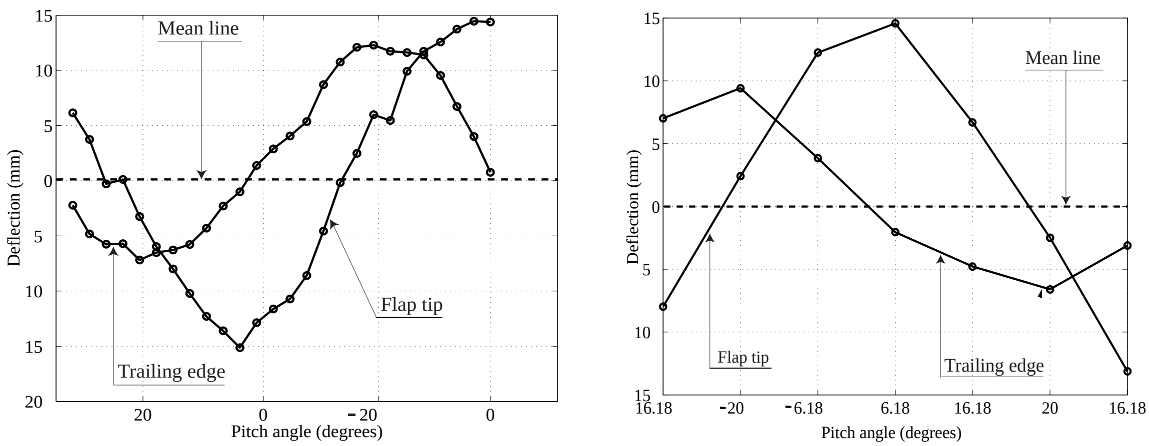


(a) **(b)**

Figure 4

(a): **Flap tip and trailing edge deflection against pitch angle for model-A. f=1 Hz, amp=10^0, U=3.56 cm/sec, St=0.37**

(b): Flap tip and trailing edge deflection against pitch angle for model-A. f=3 Hz, amp=10^0, U=12.54 cm/sec, St=0.31

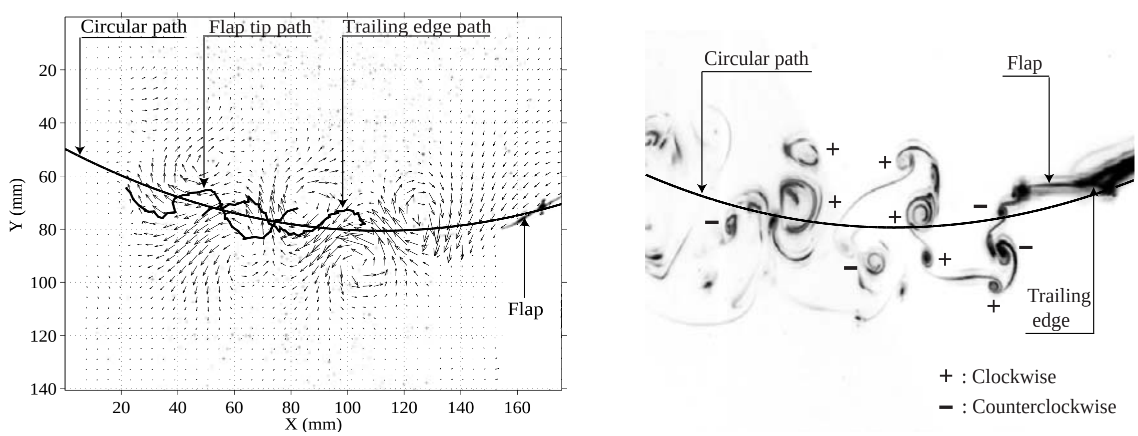


(a) **(b)**

Figure 5

(a): **Flap tip and trailing edge deflection against pitch angle for model-A. f=1 Hz, amp=20^0, U=8.17 cm/sec, St=0.31**

(b): Flap tip and trailing edge deflection against pitch angle for model-A. f=3 Hz, amp=20^0, U=25.37 cm/sec, St=0.31

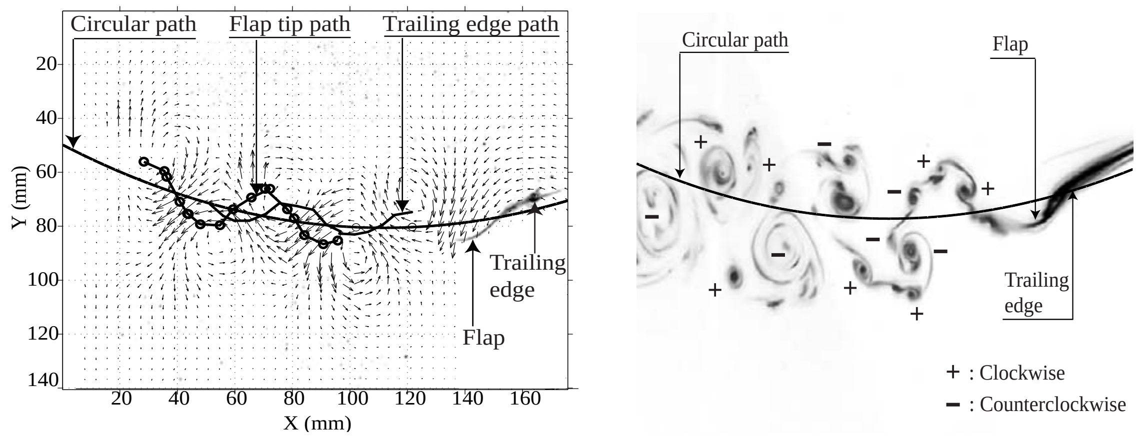


(a) **(b)**

Figure 6

(a): **PIV image: model-A. f=1 Hz, amp=10^0, U=3.56 cm/sec, St=0.37**

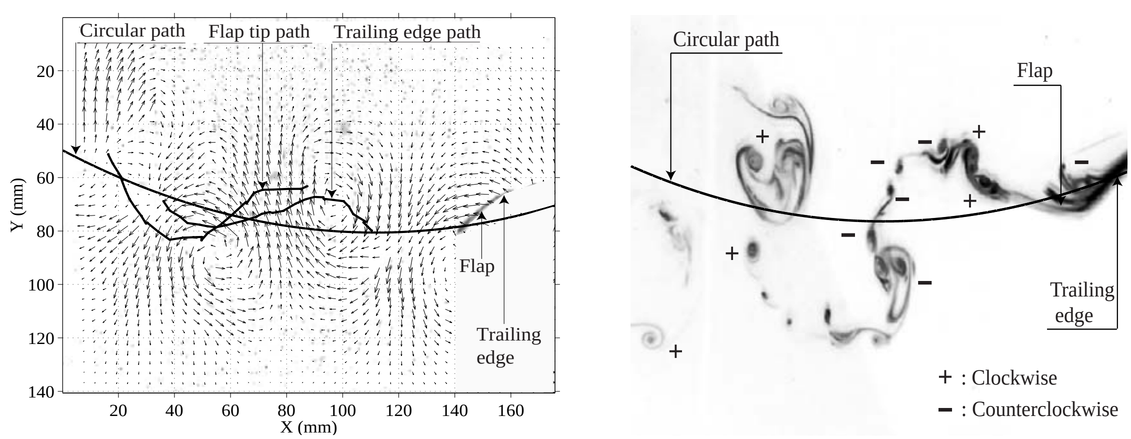
(b): **Dye visualization: model-A. f=1 Hz, amp=10^0, U=4.28 cm/sec, St=0.31**



(a) **(b)**

Figure 7

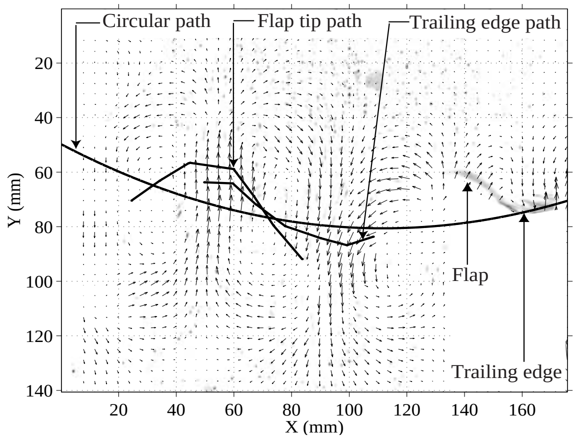
(a): **PIV image: model-A. f=3 Hz, amp=10^0, U=12.54 cm/sec, St=0.31**
(b): **Dye visualization: model-A. f=3 Hz, amp=10^0, U=11.80 cm/sec, St=0.33**

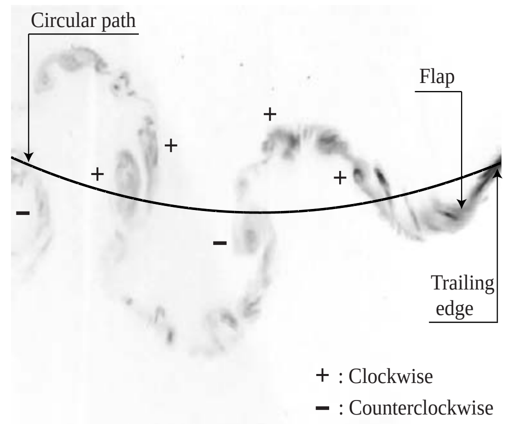


(a) **(b)**

Figure 8

(a): **PIV image: model-A. f=1 Hz, amp=20^0, U=8.17 cm/sec, St=0.31**
(b): Dye visualization: model-A. f=1 Hz, amp=20^0, U=7.85 cm/sec, St=0.33





(a) **(b)**

Figure 9

(a): **PIV image: model-A. f=3 Hz, amp=20^0, U=25.37 cm/sec, St=0.31**
(b): **Dye visualization: model-A. f=3 Hz, amp=20^0, U=24.80 cm/sec, St= 0.31**